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Optical Peregrine soliton generation in standard telecommunication fibers

Kamal Hammani [1], Bertrand Kibler [1], Christophe Finot [1], Julien Fatome [1], John M. Dudley [2] and Guy Millot [1]
[1] Laboratoire Interdisciplinaire Carnot de Bourgogne, Université de Bourgogne UMR CNRS 5209, 21078, Dijon, France
[2] Institut FEMTO-ST, Université de Franche-Comté, 25030 Besançon, France
Kamal.Hammani@u-bourgogne.fr

ABSTRACT
By combining real time characterization with cut-back measurements, we provide the first direct observation of Peregrine-like soliton longitudinal evolution dynamics and report a new effect associated with the breakup of a Peregrine soliton into two subpulses, each providing similar characteristics of localization upon finite background. Experimental results are in good agreement with simulations.

Keywords: extreme events, soliton, nonlinear fiber optics.

1. INTRODUCTION

Optical fiber systems are well-known to provide convenient platforms in which one may investigate a large variety of fascinating fundamental nonlinear structures such as solitons [1] or self-similar patterns [2]. Among the nonlinear effects, generation of extreme-value fluctuations and "optical rogue wave" localization processes currently stimulates much research interest [3]. Initial studies have focused on supercontinuum generation [4] or optical fiber amplifiers (Raman amplifiers [5] or parametric amplifiers [6, 7]) and have motivated further investigation into the initial dynamics of the supercontinuum generation process [8].

Interestingly, one of the major conclusions is that the temporal and spectral characteristics of the evolving field could be well described in terms of a particular class of nonlinear Akhmediev breather (AB) structure that undergoes periodic evolution with propagation and periodic energy exchange with a finite background [9]. One asymptotic limit of those AB is the Peregrine soliton first analytically derived in hydrodynamics by H. Peregrine as soon as 1983 [10]. Despite its existence in the mathematical literature over the past 25 years, the PS solution has only very recently been observed by means of an optical experiment [11].

We report here some recent results that complement the first experimental observation of the Peregrine soliton that we have highlighted in 2010. More precisely, we describe here the generation of PS using standard telecommunication devices and cut-back measurements of standard SMF-28 optical fiber. Direct temporal and spectral recordings of the intensity profile confirm the spatial and temporal localizations of this nonlinear structure. The impact of non-ideal conditions is also discussed.

2. EXPERIMENTAL SETUP, NUMERICAL SIMULATIONS AND ANALYTICAL MODEL

We further explore the generation of PS characteristics in optical fibers, using a much simplified setup that allow us to study the evolution dynamics over a wider range of initial conditions. The setup is sketched in Fig. 1 and is based exclusively on commercially-available telecommunication-ready components and standard silica SMF-28 fiber. In contrast to previous experiments using two narrow-linewidth lasers to create an amplitude modulated beat signal, we use here a simpler approach with a directly intensity modulated 1550 nm laser diode. Therefore, the initial field envelope is $\psi(z=0,T)=\sqrt{P_0}\left[1+\delta_{\mathrm{mod}}\cos\left(\omega_{\mathrm{mod}}T\right)\right]^{1/2}$ with δ_{mod} and ω_{mod} the intensity modulation contrast and the modulation frequency respectively. Note that a phase modulator is inserted to prevent from the deleterious consequences of Brillouin backscattering, and an erbium-doped fiber amplifier (EDFA) is used to reach average powers up P_0 to 1 W. The optical fiber is an 8.35-km long segment of SMF-28 with second and third order dispersion β_2 = -21.4 ps^2/km, β_3 = 0.12 ps^3/km, nonlinear Kerr coefficient γ = 1.2 W^{-1}/km^{-1} and 0.19 dB/km loss.

The output signal is carefully characterized both in the temporal and spectral domains by means of an optical spectrum analyzer and an ultrafast optical sampling oscilloscope (OSO – Picosolve PSO100 series) that enables the direct measurement of the picosecond intensity profile in real-time (in [11], the temporal measurements relied on a frequency resolved optical gating device). Our present setup is very convenient to monitor the precise impact of the initial conditions on this evolution. Indeed, we performed temporal and spectral characterization at $\omega_{\mathrm{mod}}/2\pi$ = 16 GHz using a value of δ_{mod} = 0.3 and twelve values of power P_0 ranging from 0.35 to 0.9 W. In particular, this range of powers enables us to study the dynamics over an extended region of the gain curve from

0.4 < a < 0.47, allowing us to approach much closer the ideal PS limit than in previous experiments performed at a = 0.42 [11]. The repetition rate was also significantly decreased (several hundreds of GHz were used in [11]).

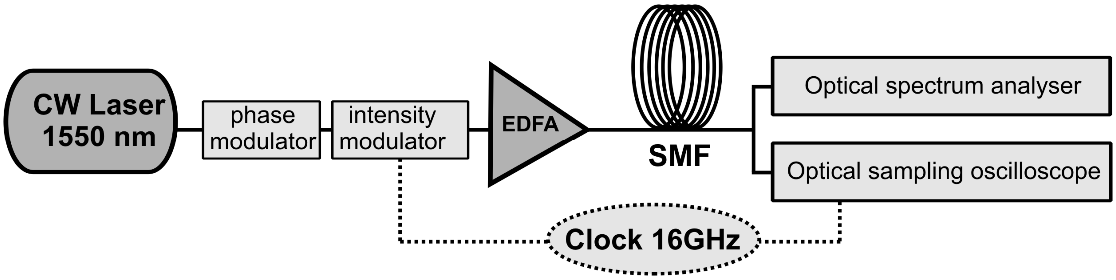

Figure 1. Experimental setup.

Our experimental results are compared to numerical simulations of the longitudinal evolution of the electric field into the optical fiber based on the well-known nonlinear Schrödinger equation (NLSE) taking into account third order dispersion, losses, Raman effects and spontaneous noise emission of the amplifier.

As this modulated field propagates along the fiber, it undergoes dynamical nonlinear compression to yield pulses that grow to high amplitude before returning to the initial state through Fermi-Pasta-Ulam (FPU) recurrence. We theoretically expect that the weakly-modulated continuous wave injected into the anomalous dispersion segment of fiber will exhibit the AB characteristics as described by the following analytic solution of the standard NLSE [12] :

$$\psi(z,T) \;=\; \sqrt{P_0}\;\frac{(1-4a)\cosh(bz/L_{NL}) + ib\sinh(bz/L_{NL}) + \sqrt{2a}\cos(\omega_{\mathrm{mod}}T)}{\sqrt{2a}\;\;\cos(\omega_{\mathrm{mod}}T)\;-\;\cosh(bz/L_{NL})}. \quad (1)$$

Breather dynamics are observed for frequencies experiencing modulation instability gain, corresponding to $0 < a < 1/2$ with $2a = [1-(\omega_{\mathrm{mod}}/\omega_c)^2]$ and $\omega_c^{\,2} = 4\,\gamma\,P_0/|\beta_2|$. The nonlinear length is $L_{NL} = (\gamma P_0)^{-1}$ and the parameter $b = [8a\,(1-2a)]^{1/2}$ determines the instability growth. Here, we are particularly interested by the asymptotic case $a \to 1/2$ that is known as the Peregrine soliton. It indeed represents the analytical limit of a wide class of NLSE solutions and it has the rational form :

$$A(z,T) = \sqrt{P_0}\left[1 - \frac{4(1+2iz/L_{NL})}{1+4(T/T_0)^2 + 4(z/L_{NL})^2}\right]\exp(iz/L_{NL}) \;\text{ where }\; T_0 = (\beta_2 L_{NL})^{1/2}. \quad (2)$$

3. EXPERIMENTAL RESULTS

3.1 Experimental results in the temporal domain

The first results we present in Fig. 2 concern the propagation dynamics as a function of power and distance. Fig. 2(a1) illustrates how the degree of dynamical compression strongly depends on initial conditions by plotting the compressed pulse peak power as a function of propagation distance for powers in the range of 0.35–0.9 W. The peak power was determined from average power measurements and the measured OSO temporal profiles. These results are illustrated by means of a false-color representation and clearly demonstrate how the distance of optimum compression decreases with higher powers. The experimental results are compared with numerical simulations in Fig. 2(a2) and show a great qualitative agreement.

For fixed input power P_0 = 0.80 W (i.e a = 0.47), Fig. 2(c) presents the temporal intensity profile measured at the distance of optimum compression L = 4.6 km. From our results, we see a clear temporally localized peak surrounded by a non-zero background. The central part of the structure has a temporal duration around 3 ps and closely follows the analytical formula of a PS as well as the numerical simulations based on the extended NLSE.

We now focus in more detail on the whole longitudinal evolution of the field corresponding to the results in Fig. 2(b) and based on a cutting of the fiber into 32 parts. We clearly observe the temporal evolution of the modulated CW field into a periodic train of ultrashort pulses standing on a continuous background. Experiments and simulations are in excellent agreement, but significantly differ from the expected PS dynamics over the optimal compression point. More precisely, we do not observe the expected return to its initial state, but rather a secondary compression phase: quite strikingly, the Peregrine soliton-like structure breaks up into two identical structures, as illustrated in Fig. 2(d).

The deviation from recurrent dynamics is attributed to the sensitivity of the propagation to non-ideal initial conditions as we approach the PS limit at higher values of a. We stress that this behaviour was not observed in previous experiments when lower values of a and more restricted propagation length were used, and thus these results represent a significant new observation. In fact, our ability to readily characterize the temporal profiles using the OSO allows us to further see that the sub-pulses are each themselves very well-fitted by the analytical form of ideal PS; comparison with the ideal PS for each sub-pulse is shown in Fig. 2(d) using $P_0 = 0.32$ W equal to the continuous background around the doublet pulses. This suggests that the Peregrine soliton profile represents an attractive structure after breakup processes, similar to behaviour of the more well-known hyperbolic secant solitons of the NLSE. However, further theoretical work will be needed to determine the precise conditions under which such breakup is initiated.

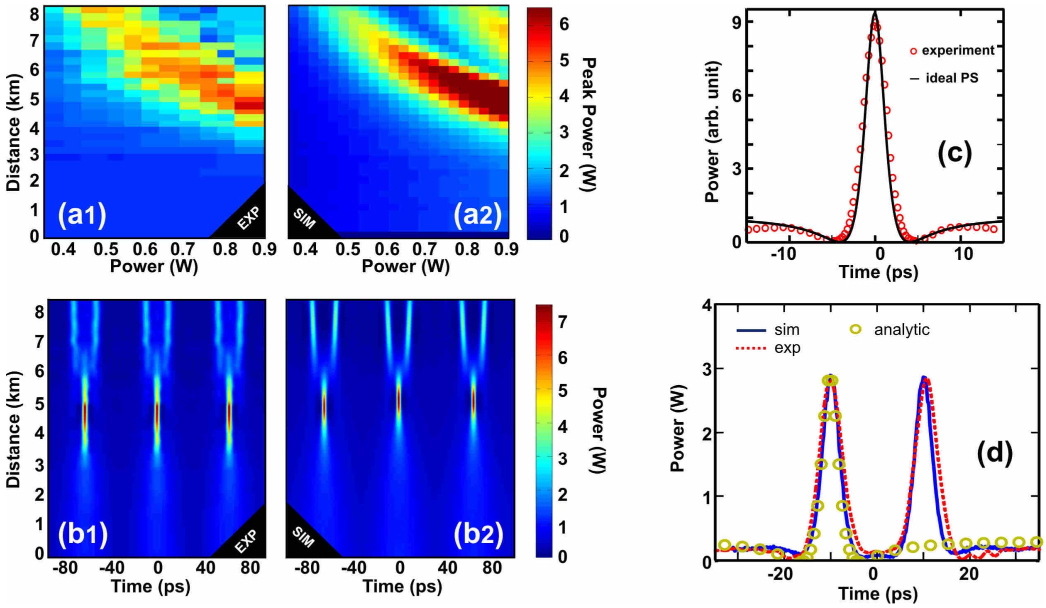

Figure. 2. (a) False color maps showing compressed peak power as a function of distance and power: (a1) experiment and (a2) simulation. (b) Evolution with distance of spectral intensities comparing experiment (b1) and simulation (b2). (c) Comparison of the temporal intensity profile measured at the optimum compression distance with P_0=0.8W. The ideal analytic PS is shown in black line. Numerical simulations yield results that are indistinguishable from the experimental data. (d) OSO signal observed at 8.4 km. Experiment (dashed red line) is compared with simulations (solid blue line) and the analytical form of PS for a subpulse (yellow circles).

3.2 Experimental results in the spectral domain

The excellent agreement observed in the temporal domain is also confirmed in the spectral domain as illustrated in Fig. 3. The experimental longitudinal scan of dynamics highlights the significant localized spectral broadening and is accurately reproduced numerically. Moreover, the spectrum recorded at the highest compression point presents a typical triangular profile when plotted on a logarithmic scale, Fig. 3(c) [13]. Additional measurements [14] (not reported here) have shown a remarkable agreement between the spectral intensity of the various harmonics and the predictions derived from the analytical AB spectrum. Let us however note that similarly to the temporal domain and due to unperfect initial conditions, the spectrum does not return back to its initial stage.

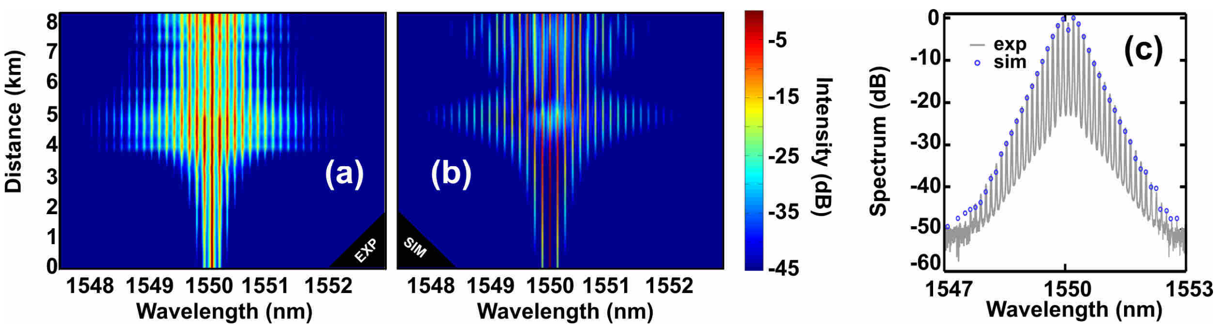

Fig. 3: Evolution with distance of spectral intensities: experiment (a) and simulation (b).
(c) Spectrum (solid grey line) at maximum compression compared with numerical results (blue circles).

4. CONCLUSIONS

We have presented experimental and numerical results showing the generation of near-ideal Peregrine solitons using a simple experimental setup with standard telecommunication components and measurement techniques. We have studied the evolution of an initially modulated field in an optical fiber towards the Peregrine soliton in a range of parameters approaching closely the ideal theoretical limit. Furthermore, our experimental setup permits us a convenient and direct characterization of the propagation dynamics through cut-back measurements. Peregrine's theoretical predictions expressed more than 25 years ago have been confirmed: the existence of a strongly localized temporal peak upon a non-zero background has been clearly demonstrated as well as, for the first time, its longitudinal localization.

The impact of non-ideal initial conditions has been studied through the longitudinal evolution of the emerging soliton dynamics, and is shown to be associated with the splitting of the Peregrine soliton into two subpulses, each exhibiting Peregrine soliton-like characteristics. Therefore, the expected FPU recurrence is not observed with our experimental parameters.

Our results stress how experiments in optics can be used to conveniently test more general theories of nonlinear waves in non-discrete soliton supporting systems. In a wider context, the fact that an initial Peregrine soliton can break up into two lower amplitude but equally strongly localized soliton pulses may have important implications for further interpretations of hydrodynamic rogue wave observations as well as establishing new links between optical and hydrodynamic extreme events [15].

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